Energy and visual comfort performance of electrochromic windows with overhangs

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Abstract

DOE-2 building energy simulations were conducted to determine if there were practical architectural and control strategy solutions that would enable electrochromic (EC) windows to significantly improve visual comfort without eroding energy-efficiency benefits. EC windows were combined with overhangs since opaque overhangs provide protection from direct sun which EC windows are unable to do alone. The window wall was divided into an upper and lower aperture so that various combinations of overhang position and control strategies could be considered. The overhang was positioned either at the top of the upper window aperture or between the upper and lower apertures. Overhang depth was varied. EC control strategies were fully bleached at all times, modulated based on incident vertical solar radiation limits, or modulated to meet the design work plane illuminance with daylight. The EC performance was compared to a state-of-the-art spectrally selective low-e window with the same divided window wall, window size, and overhang as the EC configuration. The reference window was also combined with an interior shade which was manually deployed to control glare and direct sun. Both systems had the same daylighting control system to dim the electric lighting. Results were given for south-facing private offices in a typical commercial building.

In hot and cold climates such as Houston and Chicago, EC windows with overhangs can significantly reduce the average annual daylight glare index (DGI) and deliver significant annual energy use savings if the window area is large. Total primary annual energy use was increased by 2-5% for moderate-area windows in either climate but decreased by 10% in Chicago and 5% in Houston for large-area windows. Peak electric demand can be reduced by 7-8% for moderate-area windows and by 14-16% for large-area windows in either climate. Energy and peak demand reductions can be significantly greater if the reference case does not have exterior shading or state-of-the-art static glass.

Keywords: Building simulation; Energy efficiency; Electrochromic windows; Daylighting; Control algorithms

1. Introduction

Switchable electrochromic (EC) windows rely on a nanometer-thick switchable coating on glass to reversibly change tint (clear to Prussian blue) without loss of view. For near-term products, the multi-layer tungsten-oxide coating switches in the broadband range of visible and near-IR solar radiation, is absorptive, and is best used on the inside surface of the exterior pane in a dual-pane unit so as to provide efficient solar heat gain rejection when required. This coating placement also ensures that the EC glazing layer (in combination with a low-emittance coating) does not become an interior radiator with high impinging solar radiation levels, thereby addressing thermal comfort concerns. Switching ranges for near-term products are

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fairly broad – the contrast ratio (ratio of maximum-to-minimum visible transmittance) of one known product is 12:1 with a corresponding "thermal" contrast ratio (ratio of maximum-to-minimum solar heat gain coefficient) of 4:1 to 5:1. A comprehensive review of the progress toward viable EC commercial products is given in [1]. EC products (which switch with a small applied dc voltage of 1-5 V) have been introduced into the market (starting with Flabeg GmbH in Germany in 1997) but cost and concerns over durability are still major impediments for the industry. Gasochromic windows (similar to electrochromic but are switched using an inert hydrogen gas) are also under development. Suspended particle devices are a different class of switchable devices that are similar in outward appearance to the electrochromic devices – limited data indicates that these devices may not possess the solar heat gain rejection properties nor longevity needed for long-term energy-efficient commercial building applications.

Over the past decade, many simulation studies have been conducted to estimate the energy-savings potential of electrochromic windows for various climates. Simulation studies have also been used to identify control strategies that yielded the lowest energy use. The Lawrence Berkeley National Laboratory (LBNL) conducted numerous DOE-2 commercial building energy simulation studies in the mid-1990s [e.g., 2-3], concluding that significant annual total energy savings can be obtained compared to spectrally-selective low-emittance (low-e) windows in moderate to hot climates if large-area EC windows are controlled to maintain the interior illuminance setpoint level and are combined with daylighting controls. In northern EU where commercial buildings are often heating-dominated and passive cooling is encouraged, researchers have investigated alternate strategies with and without daylighting controls where the EC is switched to provide passive heating during the winter and to reduce cooling requirements and overheating during the summer. Karlsson [4] quantified heating and cooling annual energy savings for EC windows controlled by incident vertical solar radiation limits (50-300 W/m^2) in combination with occupancy-controlled lighting and ventilation systems and a heat recovery mode regulated by interior temperatures. This mode of control yielded small savings in the northern Stockholm climate and slightly greater savings in the warmer climates of Denver and Miami given the moderate window-to-wall ratio (WWR=0.30). Gugliermetti and Bisegna [5] conducted a parametric study to identify optimum incident solar radiation limits that would yield the least total primary energy. A second set of simulations was conducted to address discomfort glare due to bright sky luminance then compared to these optimal savings. For these simulations, the daylight glare index was related to incident vertical solar radiation levels, then these limits were used to switch the EC windows for visual comfort. Total primary energy use was increased by a small margin (4-10%) on the east, south, and west facades and significantly (19%) on the north façade with the visual comfort strategy compared to the best incident solar radiation strategies. These results were given for a moderate sized window (WWR=0.33) in a typical office for three climates in Italy. The electric lights were dimmed in response to daylight with photoelectric controls. When the space was unoccupied, the EC was bleached (which unfortunately increases cooling loads) and the lights were turned off.

Simulations conducted as part of the Switchable Facades Technology (SWIFT) EU collaborative R&D project directly addressed the concerns of visual comfort. Wienold [6] conducted a Radiance-ESP-r simulation study to estimate lighting and cooling energy use savings for an electrochromic or gasochromic (GC) system combined with a Venetian blind. The switchable glazings were fully colored to reduce solar heat gains during the summer based on a incident vertical solar radiation threshold and fully bleached to admit solar radiation (passive heating) during the winter. The Venetian blind was modeled to emulate "manual" control – the blind was lowered then the slat angle was tilted to block direct sun incident on the occupant's eye and desk surface and to reduce the window luminance level to below 5000 cd/m^2. The lighting control strategy included daylight-responsive dimming controls with occupancy-based switching. Optimum vertical irradiance switching thresholds were identified through parametric runs for various EU climates. Energy savings were found to be highly dependent (factors of 2-4) on the maximum acceptable window luminance threshold, Lw-max, which unfortunately varies amongst various standards, occupant views, and applications: e.g., Lw-max=400 cd/m^2 for old cathode ray tube computer monitors versus Lw-max=4000-5000 cd/m^2 for the modern day flat-screen low-reflectance monitors. Summer energy savings for the gasochromic (Tv=0.60-0.15, SHGC=0.47-0.14) were found to be 18-28% for moderately-sized windows (WWR=0.30) and 48-55% for large-area windows (WWR=0.60) compared to a conventional window (Tv=0.75, SHGC=0.62) with the same Venetian blind control for the Rome, Stockholm, and Brussels climates. Heating energy use was in the same range as the reference case in all climates. Karlsson and LBNL simulation studies have modeled more advanced reference case windows so their estimates of energy savings were more conservative for a given climate. Platzer [7] conducted a TRNSYS-Radiance simulation study and found that switching according to room temperature yielded the least primary energy consumption but it was difficult to assess these results given the brevity of the article.

This study was conducted with several objectives. First, with the conclusion of the above simulation studies and field studies that investigated visual comfort issues associated with EC windows [8-10], practical solutions are needed that couple the EC technology with sun-blocking technologies to meet visual comfort requirements yet still maintain the energy-efficiency advantage of using EC windows over conventional windows. Wienold [ibid] studied this issue using sophisticated simulation tools and algorithms but the main control function of the EC or GC windows in his study was to avoid summer overheating as described above. In the US, mechanical air-conditioning is a foregone conclusion even in the northern climates so the control schemes must tradeoff cooling versus lighting energy use savings while addressing visual comfort requirements. This study begins to look into such solutions. Second, a more detailed study was warranted after completing a broad parametric DOE-2 simulation study [11]. This prior LBNL study quantified annual energy use and peak demand reductions resulting from unshaded EC windows controlled to optimize daylight compared to a variety of reference windows with and without manually-deployed interior shades, fixed exterior overhangs and/or fins (depending on orientation), or exterior horizon obstructions as found in built-up urban environments. This study investigates alternate exterior-shaded EC strategies which may compete with conventional exterior-shaded windows. Third, it is likely that architects will wish to combine EC windows with attached exterior elements. This study provides some indication of how best to control EC windows given typical architectural solutions and the level of performance that is likely to result.

In this study, we use the DOE-2 simulation program to estimate possible energy savings when EC windows are configured and controlled with the goal of achieving energy-eficiency and visual comfort. A south-facing window wall has been divided into an upper and lower aperture. This configuration has been identified in prior research [12] as being beneficial for energy-efficiency and comfort – the upper aperture can be used to admit or even redirect controlled daylight while the lower aperture can be used to satisfy the view and visual comfort requirements of the occupant sitting close to the window. Control strategies for the upper and lower EC apertures were parametrically varied in order to identify the best strategies that would yield the least total energy use and yet provide the best control over discomfort glare. The window was also combined with an overhang to control direct sun. The overhang was placed either at the top of the overall window wall or between the two apertures. An interior shade was not modeled with the EC window. The rationale for combining the EC with an overhang is as follows. The overhang provides some measure of direct sun protection, although it reduces the need for the EC's variable solar heat gain rejection properties during the summer period since incident irradiation levels are significantly reduced. The overhang also reduces one's need and reliance on optimal interior shade control. Prior studies indicate that manually-deployed interior shades are lowered typically because of direct sun or intolerable glare conditions then rarely readjusted [13]. Use of automatically-controlled interior shades increases the cost of the overall EC window wall system. However, the overhang is unable to block low angle direct sun in the early morning or late afternoon throughout the year nor low angle winter sun throughout the day unless the overhang is impractically deep. For these periods depending on where the occupant is sitting and the latitude, an interior shade will be required to keep the sun orb out of view of the occupant. Total primary annual energy use, peak electric demand, average annual daylight illuminance, and the average annual daylight glare index (DGI) were computed using the DOE-2 simulation program for perimeter zone private offices in Houston and Chicago. Savings are compared to the state-of-the-art static spectrally-selective low-e window with the same aperture size and zoning, overhang configuration, and daylighting control system. This reference window was combined with an interior shade which was deployed hourly to control direct sun and discomfort glare. Since the EC was not combined with an interior shade, DGI data will reflect periods of discomfort due to direct sun.

2. Method

2.1 Building module

A 4459 m^2 (48,000 ft^2) commercial office building prototype identical to that used in prior LBNL simulation studies [11] was modeled using the DOE-2.1E building energy simulation program. The prototype is a synthetic, hypothetical building, not a physically real building, with size, envelope construction, HVAC system type, operating schedules, etc. based on the mean prevailing condition among statistical samples and engineering judgment. The three-story prototype consists of a ground, intermediate

and rooftop floor. Each floor has four 139 m^2 (1500 ft^2) perimeter zones, each consisting of ten 3.04-m wide, 4.6-m deep, 2.75-m high (10x15x9 ft) private offices and a 929 m^2 (10,000 ft^2) core zone. The building was oriented true north with each façade facing the four cardinal directions. Light-weight construction was used. Insulation values for the shell were obtained from the ASHRAE Standard 90.1-1999[1]. Peak occupant density was 25.5 m^2 (275 ft^2) per person in the perimeter zones. Peak equipment loads were 8.1 W/m^2 (0.75 W/ft^2). Schedules corresponded to data from ASHRAE 90.1-1989 and other field studies. Simulations were made for a cooling-dominated location (Houston) and a heating-dominated location (Chicago). Climate data are given in Table 1.

Recessed fluorescent lighting was modeled with a lighting power density (LPD) of 12.9 W/m^2 (1.2 W/ft^2). Full LPD levels were modified by the occupancy schedule (e.g., at 8:00, 30% of full LPD was on, at 12:00, 90% of full LPD was on) in combination with daylighting controls. Heat was apportioned to the interior space (60%) and to the unconditioned plenum (40%). With daylighting controls, the perimeter zone electric lights were dimmed linearly so as to provide 538 lux (50 fc) at the work plane located 3.0 m (10 ft) from the window wall, centered on the window and at a height of 0.76 m (2.5 ft) above the floor. The electronic dimmable ballasts were modeled with a minimum power consumption of 33% and 10% minimum light output. Surface reflectances were 70% for ceilings, 50% for walls, and 20% for floors.

Five variable-air-volume systems with economizers were employed: one for each perimeter zone and one for the core zone (all three floors per orientation or core zone were controlled by one system). The heating thermostat setpoint was 21.1°C (70°F) during occupied hours with a night setback temperature of 12.8°C (55°F). Heating was provided by a gas boiler and cooling was provided by a hermetic centrifugal chiller and cooling tower.

2.2 Windows

Flush-mounted, non-operable windows were modelled in the exterior wall of each perimeter zone office. Two window sizes were modelled with a total window-to exterior-wall-area ratio (WWR) of 0.30 and 0.60. The exterior wall had a height of 3.66 m (12 ft). The window area includes the frame. (This WWR definition differs from those cited in the Introduction above, which were calculating using the interior wall area since exterior wall areas were not defined). The window positions and sizes are given in Figure 1 and Table 2. The window head height was set flush with the ceiling at 2.75 m (9 ft).

Two types of reference windows were modelled: a clear spectrally-selective low-e window and a green tinted spectrally-selective low-e window. The properties of the windows are given in Table 3. The windows were modelled with or without an interior shade. A separate shade was modelled for the upper and lower window apertures. For each hour, the shade was "manually" operated where the shade was either fully raised or lowered completely by the occupant during daylight hours if direct sun or glare was present. The shade was lowered if the heat gain from direct transmitted solar radiation exceeded 94.57 W/m^2 (30 Btu/h-ft^2) or if the daylight glare index computed using the Hopkinson Cornell-BRS formula exceeded 22 ("just uncomfortable"), which is the maximum recommended for general office work. With the shade drawn, the visible transmittance of the glazing was reduced by 65% and the solar heat gains were reduced by 40%.

The test case window was an electrochromic window with the exact window wall position and size as that of the reference window. The exterior 6-mm glazing layer had a $W0_3$ EC coating on the inboard surface. Its emittance was 0.84 on the exterior and 0.15 on the interior surface. The EC glazing was combined with a 6-mm interior clear glazing layer to form an insulating glazing unit with a 12.7-mm-wide air gap. Window properties are given in Table 3. The EC was not combined with an interior shade.

The electrochromic window was switched based on daylight or total incident vertical solar radiation levels. The upper aperture was controlled independently from the lower aperture. The window was modeled to switch linearly over a continuous (infinite) range between bleached and colored states. For the daylight control strategy, the EC transmittance was modulated so as to provide 538 lux (50 fc) at 3.05 m (10 ft) from the window wall, centered widthwise on the window, and at a work plane height of 0.76 m (2.5 ft) every hour during daylight hours. If there was insufficient daylight, the window was switched to fully bleached. If there was too much daylight, the window was switched to fully colored. For the switching strategies based on irradiance, the EC was modulated between two threshold values. The EC was bleached when the irradiance was less than or equal to 63 W/m^2 (20 Btu/h-ft^2), fully colored when the irradiance was

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[1] Increased shell insulation values mandated by ASHRAE 90.1-2004 will not alter savings results significantly because the reference and test cases alter only the window properties.

greater than or equal to 95 or 315 W/m^2 (30 or 100 Btu/h-ft^2), and partially colored when the irradiance level was between the two threshold values. The combinations of EC switching strategies for the upper and lower apertures are given in Table 4.

Table 1
Climate data

	HDD	CDD	Latitude (°)	Longitude (°)	Elevation (m)	Hrs Sun up
Chicago O'Hare	6536	2941	41.98	87.90	205	4757
Houston Hobby	1599	6876	29.97	95.35	29	4755

Notes: HDD: heating degree days base 18.3°C, 65°F; CDD: cooling degree days 10°C, 50°F; HDT: heating design temperature (99.6%); CDT: cooling design temperature (1.0%); Hrs Sun Up: number of hours sun is up.
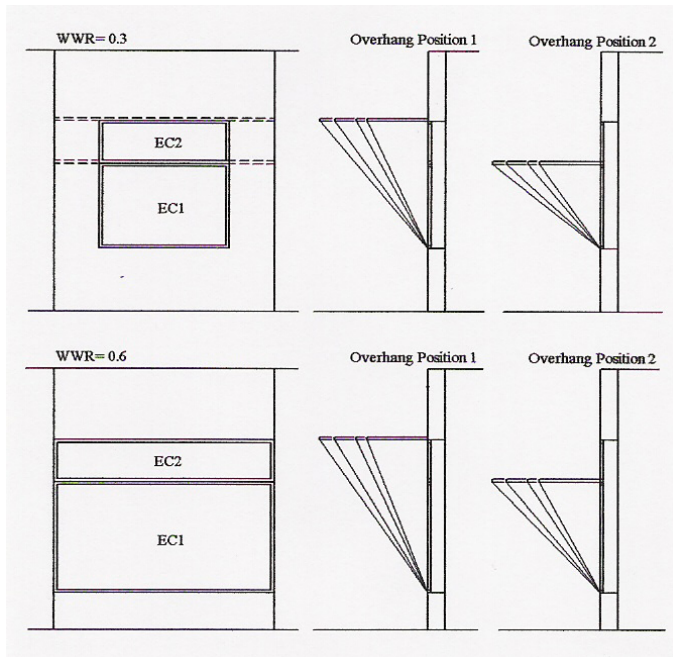

Fig. 1. Window system configurations.

Table 2
Window dimensions

Window-to-wall ratio	Exterior wall area (m^2)	Lower window			Upper window		
		width (m)	height (m)	WWR1	width (m)	height (m)	WWR2
0.3	11.15	1.83	1.22	0.20	1.83	0.61	0.10
0.6	11.15	3.05	1.58	0.43	3.05	0.61	0.17

Note: Dimensions and window-to-exterior-wall ratio (WWR) includes frame.

Table 3
Window properties

	Description		U-Factor W/m²-°K (Overall)	U-Factor Btu/h-ft²-°F (Overall)	SHGC (Overall)	SHGC (COG)	Tv (Overall)	Tv (COG)	CRI	Spacers
	Outer Layer	Inner Layer								
SS-a	Evergreen Tint	Clear SS Low-E	2.60	0.46	0.27	0.29	0.43	0.53	85.2	Alum
SS-c	Clear SS Low-E	Clear	2.60	0.46	0.34	0.38	0.57	0.71	95.4	Alum
	Bleached EC	Clear	2.76	0.49	0.37	0.42	0.45	0.56	92.7	Alum
	Colored EC	Clear	2.76	0.49	0.10	0.09	0.02	0.02	52.3	Alum

Notes: COG: Center-of-glass; CRI: Color rendering index; EC: electrochromic glazing; low-E: low emittance; SHGC: solar heat gain coefficient; SS: spectrally-selective; Alum: aluminum; Insul: insulating. U-values are given for ASHRAE winter conditions. Overall U-values are given for a window whose overall dimensions including a 7.6-cm (3-in) wide frame are 1.22x1.8 m (4x6 ft). SHGC computed for ASHRAE summer conditions. All properties were determined using WINDOW4.1 and Optics5 (v.2.0.2).

Table 4
Electrochromic window control strategies

	EC1 - lower aperture Control strategy	EC2 - upper aperture Control strategy
A	Daylight	None: always clear
B	Iv=63-315 W/m²	None: always clear
C	Daylight	Daylight
D	Iv=63-315 W/m²	Iv=63-315 W/m²
E	Iv=63-315 W/m²	Daylight
F	Iv=63-95 W/m²	Daylight

Note: Daylight: EC modulated to meet design work plane illuminance level of 538 lux; Iv is total incident vertical solar radiation on south-facing window.

2.3. Attached exterior shading

Overhangs were modelled as opaque, non-reflective surfaces. These obstructions blocked diffuse light from the sky and direct sun but reflected no light from the ground or its upper surface (no effect on interior daylighting). Three overhang depths were modelled: 0.85, 1.0, 1.3, or 1.5 m (2.79, 3.28, 4.27, or 4.92 ft). The width of the overhang was made the same width as the office module: 3.05 m (10 ft). The height of the overhang was set so that its lower surface was flush with the top of either the lower or upper framed window opening, hereafter referred to as the "between-window" or "top-of-window" overhang position.

2.4. Calculated performance

A database of total primary annual energy use (ATE), peak electric demand (PED), average annual daylight illuminance (DI), and the average annual daylight glare index (DGI) was created from EC and reference window parametric DOE-2 simulations.

Perimeter zone annual cooling electricity use was determined using system-level extraction loads converted to plant-level electricity use with a fixed coefficient of performance (COP) of 3.0. This was added to the perimeter zone annual electricity use data (includes lighting, convenience outlets, and supply and return fans for heating, heating and cooling, and float periods) to arrive at total annual electricity use. Peak electric demand (PED) was determined in a similar manner. Demand data are given for the peak condition that occurs in each perimeter zone and are non-coincident with the whole building's peak condition.

Perimeter zone annual heating energy use was determined using system-level extraction loads converted to plant-level energy use with a fixed heating efficiency factor (HEF) of 0.8. Fan electric energy

use for hours when only heating is required was not added to this quantity to enable total energy performance comparisons based on fuel type.

Total primary annual energy use (heating + electricity) was then computed using a site-to-source efficiency of 3.0 for electricity and 1.0 for natural gas. The site-to-source efficiency indicates the generating efficiency of the fuel or utility (including transmission and distribution losses) prior to its use in the simulated building.

Energy and demand savings were computed where the test and reference cases had the same window size, window position, overhang configuration, and daylighting control system. The only distinction between the two cases was that the reference case had static glazing and "non-optimal", manually-deployed interior shades while the test case had switchable EC windows. Because interior shades are rarely if never operated hourly, as was modelled for the reference case with interior shade, we used the average of the no-shade and shade case performance values to represent a reference case with non-optimal, manually-deployed interior shades. For Houston climates, the green tinted spectrally-selective low-E window was the reference case window. For the Chicago climate, the clear spectrally-selective low-E window was the reference case window.

Average annual daylight illuminance (DI) data were computed for a location 3.05 m (10 ft) from the window wall, centered widthwise on the window and at a work plane height of 0.76 m (2.5 ft). Average annual daylight glare index (DGI) data were computed using the Hopkinson Cornell-BRS formula at 1.5 m (5 ft) from the window, centered on the window, looking at the east side wall, and at a height of 1.22 m (4 ft) above the floor. The upper and lower apertures were computed as separate sources contributing to the total DGI value.

3.0. Results

For each climate, performance data are given in Figures 2-3 for the two window sizes, six EC control algorithms (see Table 4 for key), overhang position, and overhang depth. The lines connecting the points (e.g., control scheme F and SS-a case) are meant to ease grouping of the datasets and are not meant to imply a relationship between distinct cases. Total primary annual energy use, peak electric demand, energy use savings, and demand savings are shown on the plots. Energy use and demand data are given per unit floor area. The energy savings data are meant to answer the question: "If the manually-deployed interior shade and static glass are substituted for EC glass, how much savings will result?" The savings data do not tell the reader which of all the test configurations yields the lowest energy use or peak demand – the absolute data provides the reader with this answer. Average annual daylight illuminance and the average annual daylight glare index are also shown. For the average annual DGI, values of 10, 16, 22, and 28 correspond to "just imperceptible", "just acceptable", "just uncomfortable", and "just intolerable" levels of glare, respectively, given a side view of the window. The clear spectrally-selective low-e reference case without and with shade are designated as SS-a and SS-b, respectively. Similarly, the tinted reference cases are designated as SS-c and SS-d.

To identify the "best" EC solution, the reader must assign relative importance to the various performance metrics then combine the metrics to determine whether the solution yields sufficient benefits. In this analysis, we strived to identify solutions that result in a) the lowest level of discomfort glare (minimize DGI), b) adequate daylight levels to offset electric lighting needs, dispel gloom, and provide controlled interior brightness (i.e., DI closest to the desired setpoint of 538 lux), and c) lowest annual energy use (minimize ATE). The significance of differences in DGI and DI between configurations is difficult to judge given that these are average annual values. Note however that although most DGI values shown in Figures 2-3 are below 10 (="just imperceptible"), these averages likely mask infrequent but intolerable discomfort glare. Therefore, even small differences in DGI ($\Delta \cong 1.0$) can be judged significant. Peak demand does play a role in this analysis, but not in the identification of the best overall solution since our perspective was that the EC control strategy can be temporarily toggled to a demand response or cost-reduction mode by the facility manager in lieu of the normal operating mode which is designed to address visual comfort and energy-efficiency requirements.

Notice that the ranking of the EC control algorithms is the same between the various overhang depths. For example, if the DGI of control algorithm A is greater than control B for an overhang depth of 0.85 m, then the same will be true for an overhang depth of 1.3 m. In general, ATE, PED, DGI, and DI all decrease as the depth of the overhang increases, with some exceptions with DGI.
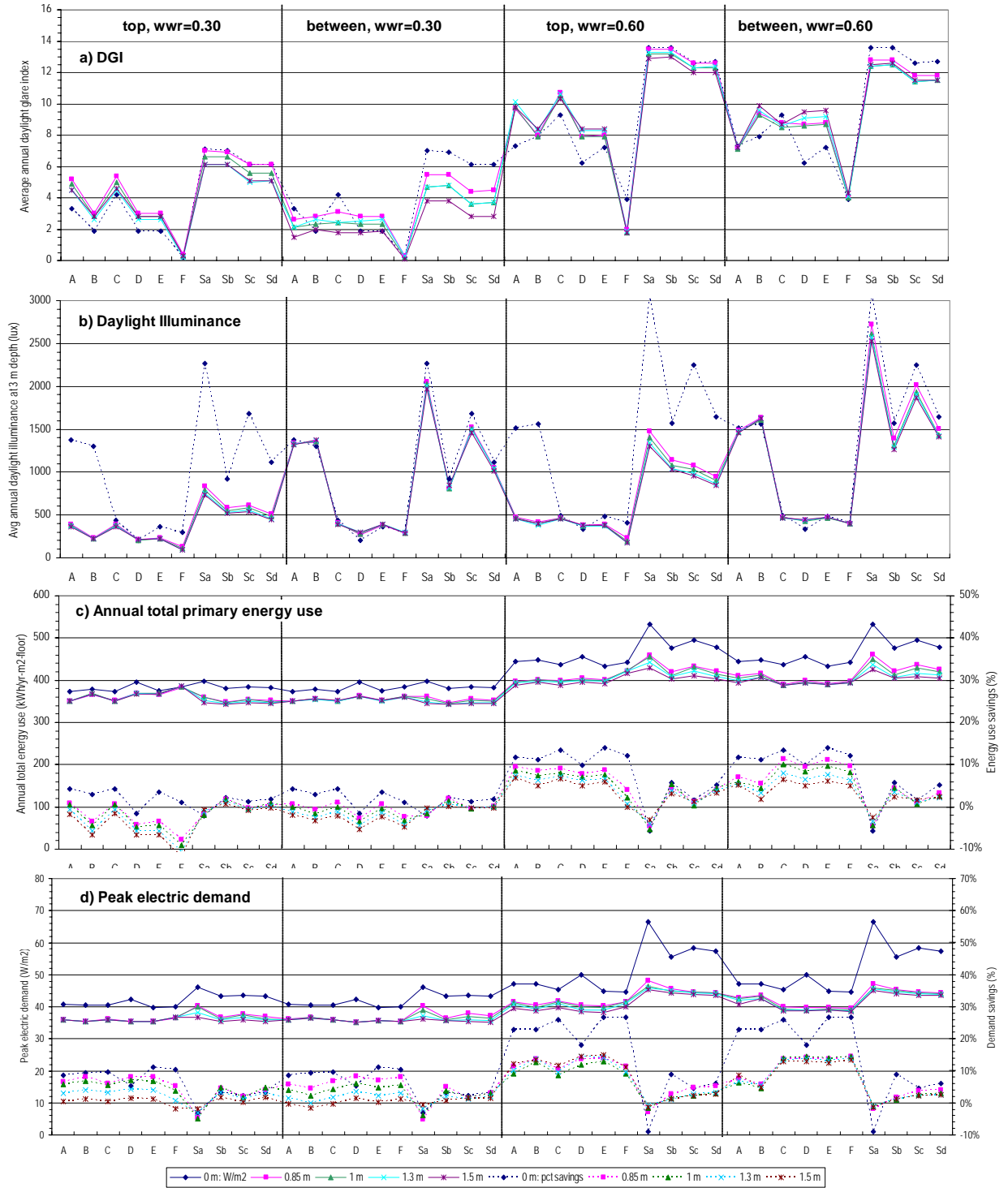
Fig. 2. Chicago. a) Average annual daylight glare index, b) average annual daylight illuminance, c) total primary annual energy use, and d) peak electric demand for a south-facing private office with EC windows controlled by schemes A-F or static spectrally-selective low-E reference windows (Sa-Sd). Overhang depth is varied from 0 m to 1.5 m. Case shown from left to right. Case 1: WWR=0.30, top-of-window overhang, Case 2: WWR=0.30, between-window overhang, Case 3: WWR=0.60, top-of-window overhang, Case 4: WWR=0.60, between-window overhang.
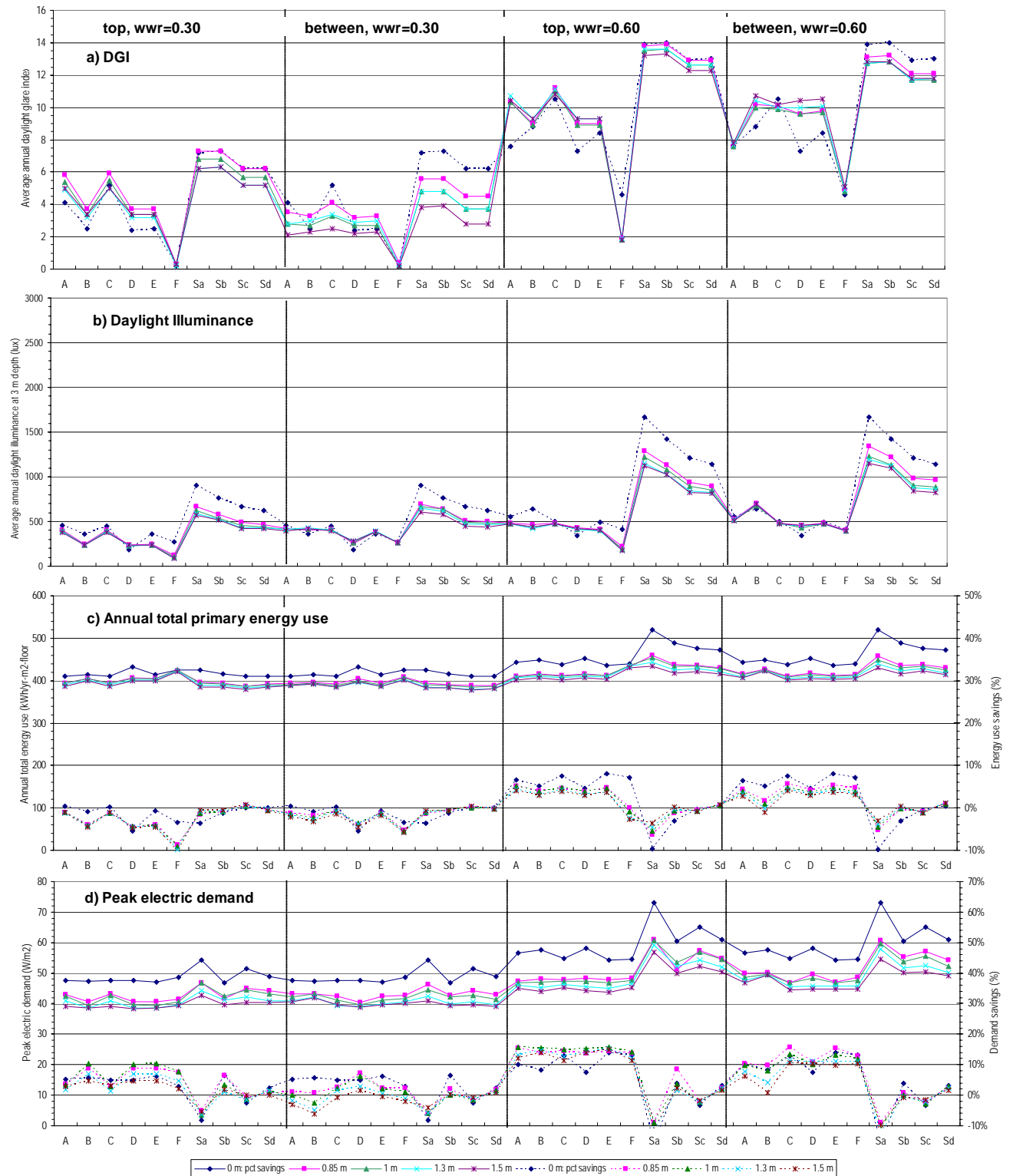
Fig. 3. Houston. a) Average annual daylight glare index, b) average annual daylight illuminance, c) total primary annual energy use, and d) peak electric demand for a south-facing private office with EC windows controlled by schemes A-F or static spectrally-selective low-E reference windows (Sa-Sd). Overhang depth is varied from 0 m to 1.5 m. Case shown from left to right. Case 1: WWR=0.30, top-of-window overhang, Case 2: WWR=0.30, between-window overhang, Case 3: WWR=0.60, top-of-window overhang, Case 4: WWR=0.60, between-window overhang.

3.1. Hot climate: Houston

With a moderate-area exterior-shaded window (WWR=0.30), DGI is lowest with the EC control scheme F. To increase daylight and to combat gloom with the EC case, DI can be increased from 89-122 lux for the top-of-window overhang case (of varying depths) to 260-263 lux levels for the between-window overhang case with no negative impact on DGI. With this latter scheme, EC annual energy use is increased by 5-6% compared to the reference case, while visual comfort (DGI) is significantly improved. Average annual DGI levels were 0.2-0.4 with the EC windows versus 2.8-4.5 with the reference windows. Peak demand reductions are greatest (7%) with control scheme D by a small margin between all control schemes.

With a large-area exterior-shaded window (WWR=0.60), there are significant differences in DGI between the EC top-of-window and between-window overhang cases. The top-of-window overhang with EC control scheme F yields the lowest DGI (1.8-1.9 given the range of overhang depths) but it also yields the lowest DI (174-222 lux). The between-window overhang case raises the DI range to 394-401 lux, but DGI is also raised to a range of 4.8-5.1. Fine-tuning the EC control thresholds to that between control schemes E (63-315 W/m^2) and F (63-95 W/m^2) does not allow one to attain the 538 lux desired average and it significantly increases DGI. The best solution depends on one's relative importance of glare control versus interior brightness and outside view. Total primary annual energy use is relatively unperturbed by these on-goings, the maximum difference in ATE between all EC cases is 34 kWh/yr-m^2-floor (10.8 kBtu/yr-ft^2-floor) or ~8%. For the case that yields the lowest DGI (top-of-window overhang, scheme F), annual energy use is increased by 0-3% compared to the reference case, while peak demand reductions are 11-16% and are insensitive to control schemes. Relaxing DGI constraints raises energy savings to 3-5% for the between-window overhang scheme F case.

With no overhang, a moderate-area window, and EC control scheme F, the average annual daylight illuminance and daylight glare index are the same as the best-case EC window with a between-window overhang. Annual energy use savings is increased by 4% and peak demand is increased by 12% compared to the EC exterior shaded case. One could argue that the overhang provides minor benefit when combined with the EC window except for control of direct sun and the reduction of peak demand. With the large-area window, an overhang provides significant benefits: with no overhang and EC control scheme F, DGI, DI, ATE, and PED are all increased significantly.

3.2. Cold climate: Chicago

With a moderate-area or large-area exterior-shaded window, the same trends and conclusions can be drawn for Chicago as for Houston. The EC with control scheme F delivers significantly better control of discomfort glare compared to the reference cases but also reduces interior daylight illuminance levels. For a moderate-area window with a between-window overhang (of varying depths), energy use is increased by 2-5% and peak demand is reduced by 1-8%. For large-area windows, energy savings are 0-4% or 5-10% with a top-of-window or between-window overhang, respectively, while peak demand reductions are 13-14% and 14%, respectively. Note that while the reference window DGI trends are similar to that of Houston (latitude 30°N), DI is significantly greater for the between-window overhang cases (SS-a and SS-c) in Chicago (latitude 42°N) due to the lower-angle sun paths of more northern climates. So for the large-area window, the best EC solution also exerts greater control over interior daylight illuminance levels.

4.0. Discussion

The key objective of this work was to identify practical solutions that both meet comfort requirements and deliver energy savings. There are several issues that require discussion. First, as mentioned earlier, horizontal projections such as overhangs do not block the orb of the sun during the critical periods when the sun is low on the horizon. For example, on clear sunny days between October 21 though February 21 in Chicago, even with a 1.5-m (5-ft) deep overhang on the south facade, direct sun is in one's view all day (December 21: ~7:30-16:30, October 21 or February 21: 6:40-17:20 sun is in view) if one is facing south or several hours of the day if one is facing east or west and seated close to the window. Thereafter, the overhang blocks direct sun during progressively earlier or later hours, until by the equinox (6 months between March 21-September 21), direct sun is always blocked throughout most daylight hours (6:00-18:00). Since EC windows cannot block the direct sun orb (minimum Tv=0.02), one must conclude that even with overhangs, another type of shade, most likely an interior Venetian blind will be required. The

degree of requirement is dependent on the frequency of clear sky conditions during this 6-month "winter" period, the position of the occupant's eye, or the presence of horizon obstructions. If the skies are fairly overcast throughout this period or the occupant can reposition their task to avoid direct views of the sun, then the EC alone may suffice. If there are trees, mountains, or urban obstructions with a 20-40° vertical angle, then the EC alone may suffice but the benefit of the EC glazing will be diminished. If not, then an interior shade is almost certainly required (Figure 4). To increase daylight, one could install a manually-operated Venetian blind with an EC in the lower aperture and install a sun-blocking, daylight-redirecting system with an EC in the upper aperture. With this solution, the occupant controls direct sun, exterior view, and privacy via the lower aperture, while the upper aperture is used to offset electric lighting requirements. Use of light shelves will also improve daylighting performance. A second, more costly solution would be to couple an EC window with an automated interior Venetian blind.

Summer solstice	Equinox	Winter solstice

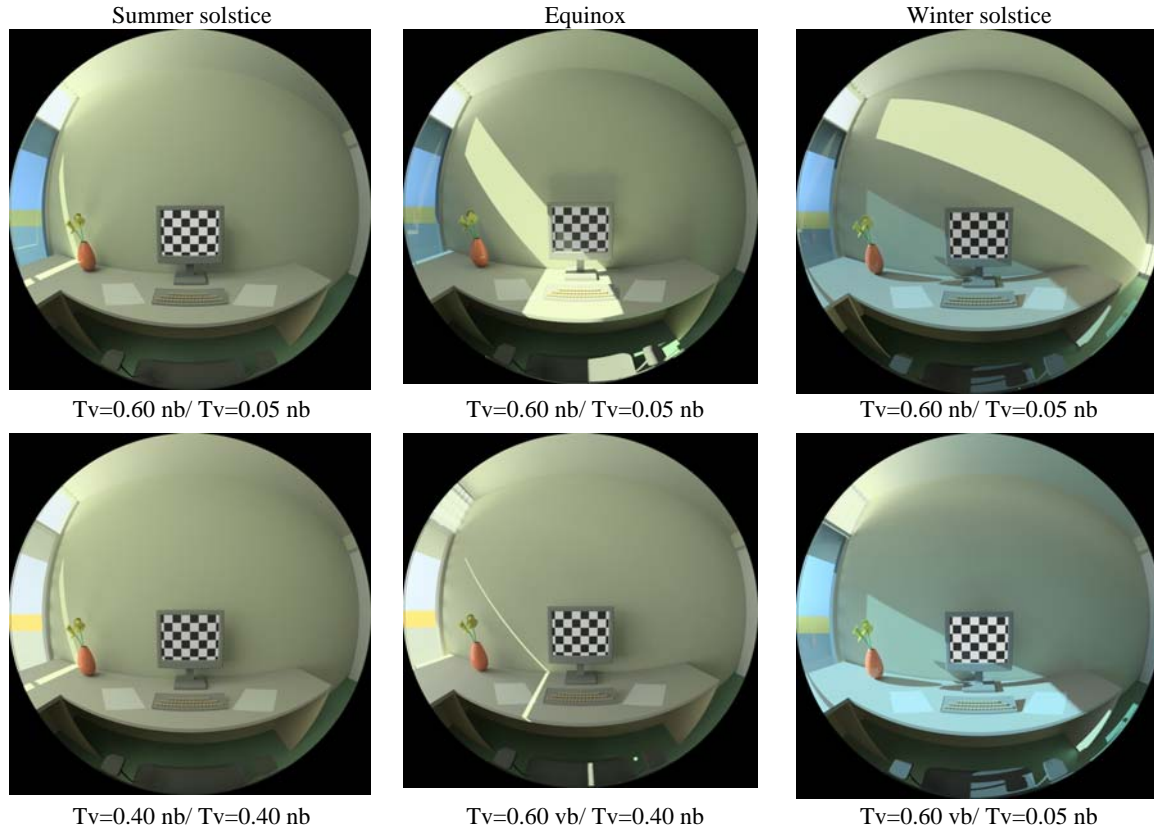| Tv=0.60 nb/ Tv=0.05 nb	Tv=0.60 nb/ Tv=0.05 nb	Tv=0.60 nb/ Tv=0.05 nb
Tv=0.40 nb/ Tv=0.40 nb	Tv=0.60 vb/ Tv=0.40 nb	Tv=0.60 vb/ Tv=0.05 nb

Fig. 4. Illustration of direct sun patterns generated by Radiance simulations of a private office space with overhang under clear sunny skies at 11:30 on the summer solstice (left), equinox (middle), and winter solstice (right) in Chicago. The top row shows the upper aperture EC at Tv=0.60 without Venetian blinds ("nb") and the lower aperture EC at Tv=0.05. The bottom row shows the upper aperture EC at Tv=0.60 with Venetian blinds ("vb") for the equinox and winter solstice conditions (none needed for the summer solstice condition) and the lower aperture EC at Tv=0.40 to reduce sky glare on the equinox and summer solstice condition and at Tv=0.05 for direct sun control on the winter solstice condition. The office is identical to the DOE-2 simulation model with a WWR=0.60 with a view centered on width of the window wall at a 1.2 m (4 ft) height and 1.52 m (5 ft) distance from the window.

Second, while comfort is of critical concern, energy-efficiency is the primary concern to public agency stakeholders and utilities investing in EC technologies today. Definition of the reference case can significantly affect one's estimate of potential energy-savings derived from EC windows. If comfort requirements must be met and the reference case is conservative (same overhang configuration as the test case), then EC energy savings are modest (10% in Chicago and 5% in Houston, control scheme F) for only large-area windows. If comfort requirements must be met (control scheme F) and the reference case does

not have an exterior overhang, then EC energy savings can be more significant for both moderate- and large-area windows. For example, for an EC with a 0.85-m deep overhang, EC energy savings are 7% for moderate-area windows and 16-21% for large-area windows in Chicago. In Houston for the same cases, energy savings are 0% for moderate-area windows and 9-13% for large-area windows. The reference case glazing is conservative given what has been installed in the existing building stock. If EC windows become practical for retrofit applications, then energy savings compared to more conventional single-pane and double-pane, tinted, and reflective glazings will be even more significant.

Third, the EC gains its comfort advantage over conventional window solutions by reducing discomfort glare due to bright sky light with its variable tint. It does so while preserving exterior view. Further study is required to determine if EC windows and various control strategies improve overall visual comfort and visual performance. Luminance contrast ratios, window luminance, and computer display visibility should be examined. The DOE-2 modeling of discomfort glare provides us with a broad view of the trade-offs between energy savings and comfort – more detailed analysis is warranted. One solution that has not been explored in this analysis is the combination of interior Venetian blinds with EC windows. A full-scale field study has been conducted to monitor the performance of a zoned EC window wall, similar to that modelled in this study, with Venetian blind compared to a spectrally-selective low-e reference window with Venetian blind [14]. Monitored data suggests that for flush-façade designs, EC windows can yet provide significant energy-efficiency benefits if controlled properly.

5.0. Conclusions

DOE-2 building energy simulations were conducted to determine if there were practical architectural and control strategy solutions that would enable electrochromic (EC) windows to significantly improve visual comfort without eroding energy-efficiency benefits. EC windows were combined with overhangs since opaque overhangs provide protection from direct sun which EC windows are unable to do alone. The window wall was divided into an upper and lower aperture so that various combinations of overhang position and control strategies could be considered. The overhang was positioned either at the top of the upper window aperture or between the upper and lower apertures. Overhang depth was varied. EC control strategies were fully bleached at all times, modulated based on incident vertical solar radiation limits, or modulated to meet the design work plane illuminance with daylight. The EC performance was compared to a state-of-the-art spectrally selective low-e window with the same divided window wall, window size, and overhang as the EC configuration. The reference window was also combined with an interior shade which was manually deployed to control glare and direct sun. Both systems had the same daylighting control system to dim the electric lighting. Results were given for south-facing private offices in a typical commercial building.

In hot and cold climates such as Houston and Chicago, EC windows can significantly reduce the average annual daylight glare index (DGI) and deliver significant annual energy use savings if the window area is large. The control strategy that provided the lowest DGI was control scheme F where the lower aperture is modulated in proportion to incident solar radiation and the upper aperture is modulated for daylight. With a between-window overhang of moderate depth (0.85 m or 2.79 ft), average annual daylight illuminance levels were below the desired design illuminance level of 538 lux (~275 lux for moderate-area windows and 400 lux for large-area windows) so interior brightness may be compromised. Total primary annual energy use was increased by 2-5% for moderate-area windows in either climate and decreased by 10% in Chicago and 5% in Houston for large-area windows. Peak electric demand can be reduced by 7-8% for moderate-area windows and by 14-16% for large-area windows in either climate using alternate control schemes that are toggled on by the facility manager when in a demand-response mode. Energy and peak demand reductions can be significantly greater if the reference case does not have exterior shading or state-of-the-art glass.

The overhang cannot block low angle direct sun, so the EC window will likely also require an interior shade. To improve daylighting performance, separate interior shades could be specified for the upper and lower apertures. A sun-blocking daylight-redirecting technology coupled with the EC in the upper aperture would eliminate the need for the upper aperture interior shade and would further improve daylighting performance. Alternate EC strategies coupled with an interior shade and without exterior shades should be considered in future work.

Acknowledgments

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